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The AMLCD cockpit: promise and payoffs *

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ABSTRACT

The active matrix liquid crystal display (AMLCD) has become the preferred flight instrument technology in avionics multifunction display applications. Current bubble canopy fighter cockpit applications involve sizes up to 7.8 x 7.8 in. active display. Dual use avionics versions of AMLCD technology are now as large as 6.7 x 6.7 in. active display area in the ARINC D sized color multifunction display (MFD). This is the standard instrument in all new Boeing transport aircraft and is being retrofitted into the C-17A. A special design of the ARINC D instrument is used in the Space Shuttle cockpit upgrade. Larger sizes of AMLCD were desired when decisions were made in the early 1990s for the F-22. Commercial AMLCD technology has now produced monitors at 1280 x 1024 resolution (1.3 megapixels) in sizes of 16 to 21 in. diagonal. Each of these larger AMLCDs has more information carrying capacity than the entire F-22A cockpit instrument panel shipset, comprising six separate smaller AMLCDs (1.2 megapixels total). The larger AMLCDs are being integrated into airborne mission crewstations for use in dim ambient lighting conditions. It is now time to identify and address the technology challenges of upgrading these larger AMLCDs for sunlight readable applications and of developing concepts for their integration into advanced bubble canopy fighter cockpits. The overall goals are to significantly increase the informational carrying capacity to bring both sensor and information fusion into the cockpit and, thereby, to enable a significant increase in warfighter situational awareness and effectiveness. A research cockpit was built using specialized versions of the IBM 16.1 in and two smaller 10 in. AMLCDs to examine human factors and display design issues associated with these next-generation AMLCD cockpit displays. This cockpit was later upgraded to allow greater reconfigurability and flexibility in the display hardware used to conduct part-task mission simulations. The objective optical characterization of the AMLCDs used in this simulator and the cockpit design are described. Display formats under consideration for test in this cockpit are described together with some of the basic human factors engineering issues involved. Studies conducted in this cockpit will be part of an ongoing joint effort of the hardware-focused aerospace displays team and the pilot-focused human factors team in the Air Force Research Laboratory's Crew System Interface Division. The objective of these studies is to ascertain the payoffs of the large AMLCD promise in combat cockpits.

Keywords: active matrix liquid crystal display, AMLCD, cockpit, displays, electronics, evaluation, human factors, large flat panels, situational awareness, test

1. INTRODUCTION

Active-matrix liquid-crystal displays (AMLCDs) are increasingly finding their way into the design of modern cockpits, both military and civil. These displays have many advantages (and some disadvantages) relative to the technology they are replacing: in most cases, cathode ray tubes (CRTs). A reconfigurable cockpit simulator has been constructed at the Air Force Research Laboratory in which the displays can consist entirely of AMLCDs, CRTs, or a mix of these technologies. AMLCDs vary widely in cost, size, capability, ruggedization, and technology maturity. One purpose of this simulator is to test a variety of cockpit design issues associated with AMLCDs. These issues include everything from basic perceptual characteristics to the human factors of display symbology.

There is a very broad span of technology represented in modern cockpit displays. In the general aviation community, electromechanical or "steam" gauges are still the norm. Commercial aviation cockpits contain a mix of electromechanical, flat-panel, and now even head-up displays (HUDs), depending on the aircraft in question. Like commercial aviation, military aviation also currently takes advantage of a mix of display technologies. Older transport aircraft tend to rely mostly on electromechanical displays. Fighter aircraft and newer transport aircraft incorporate HUDs and glass cockpit

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designs. AMLCDs are an increasingly important display technology used in these glass cockpits.

Not only are a wide range of display technologies found in today's cockpits, the range of advancement and capabilities within each technology is also extensive. AMLCDs are a good example of this: display addressability, usable viewing angle, and color characteristics of cockpit AMLCDs vary widely. As with other display technologies, there are large price-performance tradeoffs to be considered when incorporating AMLCDs into cockpit designs. As AMLCD technology improves and becomes cheaper, it is more and more likely to become a mainstay in modern glass cockpits. A continuing need exists for research into how best to employ this technology in the cockpit, how to best maximize its advantages and minimize its disadvantages, and to explore human factors issues associated with pilots' use of these displays. There is a need for applied research to examine and optimize the effectiveness with which AMLCDs communicate information to the pilot. This need becomes greater as these displays increase in pixel density and amount of information that can be displayed. Work has recently been completed at Wright-Patterson AFB on the design and implementation of a testbed to be used in examining these issues and tradeoffs. A research simulator, hereafter referred to as the AMLCD Research Cockpit, was constructed to incorporate a range of AMLCD technologies in a configuration to allow applied and exploratory human factors research into issues both basic (e.g., fundamental perceptual issues) and advanced (e.g., optimization of information format for use by the pilot). It was later upgraded to allow flexibility in use and the inclusion of other technologies (e.g., CRTs). The purpose of this paper is to describe the concept and design of the AMLCD Research Cockpit, its intended uses, and the benefits to be gained from employment of AMLCDs in aircraft both real and simulated.

2. DISPLAY SELECTION AND COCKPIT LAYOUT

Research cockpits have heretofore used CRT technology as an affordable means of simulating the visual interface of both operational and notional air- and spacecraft instrument panels. Flat panel displays in small and medium sizes (3 to 10 in.) have now begun to appear in significant numbers in operational aircraft. Thus, it is necessary to bring research cockpits up to date to enable the exploration of advanced crew-system interface concepts using the large (greater than 10 in.) flat panel display technologies now available.

Subjective (and perhaps performance) results in the use of these displays are likely to be affected by the fact that AMLCD and other new flat panel display technologies form images that are rectilinear flat rather than curved. Also, flat panel display technologies form images in the form of a two dimensional array of pixels, rather than a field of scanned lines. Acceptability issues such as raster modulation, raster structure (e.g., interlaced, non-interlaced), and luminance uniformity that normally affect CRTs are replaced in large AMLCDs by issues such as usable viewing angle. Unless the research cockpit incorporates AMLCD technology, screen designs, including dynamic as well as static features and effects, cannot be optimized in human factors studies to reflect the realities of the display hardware technologies that will be used to implement the laboratory results.

Photographs of two configurations of the AMLCD Research Cockpit layout are illustrated in Figure 1. The photo on the left in this figure shows an all-AMLCD configuration (one 16.1 inch, two 10.4 inch). The photo on the right shows a mix of technologies: one large 16.1 inch AMLCD surrounded by four smaller CRTs (two 6 x 6 in. XKD Corp. Model MFD6060 and two Sony 4 x 3 in.). The AMLCD displays used are all ruggedized versions of commercial products designed for integration into computer monitors, laptops, and automobiles. Sunlight readable displays suitable for use in fielded combat aircraft are not necessary as the research cockpit sits in a climate controlled facility with dimmable room lighting. However, the displays used are, in fact, being used in aircraft crewstation applications where interior lighting is dim (e.g., crewstations in the rear of the aircraft) or where the instrument panel can be shielded from both shafting sunlight and from most ambient illumination (e.g., a transport cockpit). Thus, it is reasonable to anticipate that the displays selected, while significantly larger than those in operational cockpits, can be developed for production should the need arise.

Figure 1. Photographs of the AMLCD Research Cockpit: all-AMLCD on the left, mixed technologies on the right.

The configuration on the left in Figure 1 was designed to have up to three different sized AMLCDs (one 16.1, two 10.4, two 5.4 in.) providing up to 258 square inches of active display area. The central display is a 16.1-inch diagonal color 1280 x 1024 resolution in landscape. The 16.1 inch is a custom design display for the AFRL Visual Display Systems Branch involving ruggedized packaging by L3 Communications using a commercial monitor designed by IBM at its Armonk NY design facility and manufactured under IBM control in its DTI AMLCD fabrication facility (DTI is a joint IBM/Toshiba AMLCD foundry located in Japan). It is possible to mount two displays above the central display that are 5.4 inch diagonal, 320 x 240 resolution, color AMLCDs in landscape packaged by Honeywell using Sharp glass. The displays on either side of the central display are 10.5 in. diagonal, 480 x 640 resolution, color AMLCDs manufactured by Sharp (landscape-design notebook computer displays mounted in portrait orientation) and packaged like a prototype flight instrument by Interstate Electronics. The side displays can be mounted on wing panels that are hinged with the front panel to provide for adjustable horizontal viewing angle. These side displays may also be mounted so the vertical viewing angle can be adjusted by pivoting the display about a horizontal axis. Similarly, the center display may be placed in a mounting bracket that allows both horizontal and vertical viewing angle adjustment.

An overview of the displays examined for the AMLCD Research Cockpit are listed in Table I.

Table I. Overview of AMLCDs selected for Air Force Research Laboratory AMLCD Research Cockpit.

Size	**Resolution**	**AMLCD Manufacturer**	**AMLCD Integrator**	**Comment**
Horizontal x Vertical (Diagonal)	**H x V Format**			
(inches)	**(color pixels)**			
12.5 x 10 (16.1)	1280 x 1024	IBM	L3 Communications	Custom rugged packaging
6.24 x 8.31 (10.4)	480 x 640	Sharp	Interstate Electronics	Packaged notebook display
4.3 x 3.2 (5.4)	320 x 240	Sharp LQ6RA52	Honeywell	Ruggedized automotive display

The configuration shown in Figure 2 uses just the 16.1 in AMLCD display. This one large AMLCD has more information carrying capacity than the entire head down display suite in the F-22A in terms of raw pixels. Left and right of the large AMLCD are four smaller CRTs of 6x6 and 4x3 size.

2.1. Description of the AMLCDs in the AMLCD Research Cockpit

Table II provides a list of the general specifications for the three different sized AMLCDs. It is important to note that each display was constructed from a commercial consumer-grade AMLCD glass stack.

Table II. Specifications for AMLCDs used.

	16.1 in. AMLCD	10.4 in. AMLCD	5.4 in. AMLCD
Display Integrator	L3 Communications	Interstate Electronics	Honeywell
AMLCD Manufacturer	IBM in its DTI foundry	Unknown	Sharp
Active Area (in., H x V format)	12.5 x 10	6.24 x 8.31	4.3 x 3.2
Orientation	landscape	portrait	landscape
Area (square inches)	125.0	52.5	13.8
Aspect Ratio	5:4	3:4	4:3
Addressable Color Pixels	1280 x 1024	480x 640	320x240
Pixel Density (color pixels/in.)	102.4	76	75
Resolution (pixels, H x V format)	SXGA (1280 x 1024)	VGA (480 x 640)	QVGA (320 x 240)
Interface	RGB-Multi-sync	NTSC-HV	NTSC - RGB-C
Ruggedized	yes (AFRL special design)	no	yes
Black Matrix	yes	yes	yes
Pixel Structure	RGB stripe	RGB stripe	RGB stripe
Bezel Buttons	yes (AFRL special design)	no	no
Built-in-test (BIT)	yes	no	no
Temperature, operating (^{o}C)	0 to +55	N/A	-30 to 85
Temperature, storage (^{o}C)	-40 to +85	N/A	-55 to +90

2.1.1. L3 Communications custom integrated 16.1 in. AMLCD (special design fabricated for AFRL research)

This display was acquired from L3 Communications, located in Apharetta, GA (770-752-7000). L3 Communications made this display in 1996 by taking IBM/DTI 16-inch glass stack and ruggedizing it for an avionics application. The light source is a high-luminance serpentine backlight. The IBM/DTI glass stack is sandwiched between two pieces of heavy-duty cover glass and the top piece has a high-grade anti-reflective coating. See Figure 3 for a schematic of the 16-inch display. This ruggedized display weighs about 35 pounds.

The 16.1 in. display has 21 lighted, programmable bezel buttons around the perimeter. Each button includes a small reflective LCD with a 20H x 20V dot matrix array for text or icon display. An RS-232 interface provides the link back to the computer for these buttons. The 16 in. display uses a Pixelvision Topaz interface card supporting pixel rates up to 135 MHz. It provides a multisync interface for display resolutions from 640 x 480 through 1280 x 1024. It supports a progressive scan vertical refresh up to 76 Hz for 1280 x 1024 mode. The display has external brightness and contrast adjustments and an on-screen pop-up menu for adjustments such as size and position. A photograph and a schematic drawing of the 16.1 in. AMLCD designed by L3 specifically for AFRL research are shown in Figures 2 and 3.

Figure 2. Cockpit simulator display (16.1 in.).

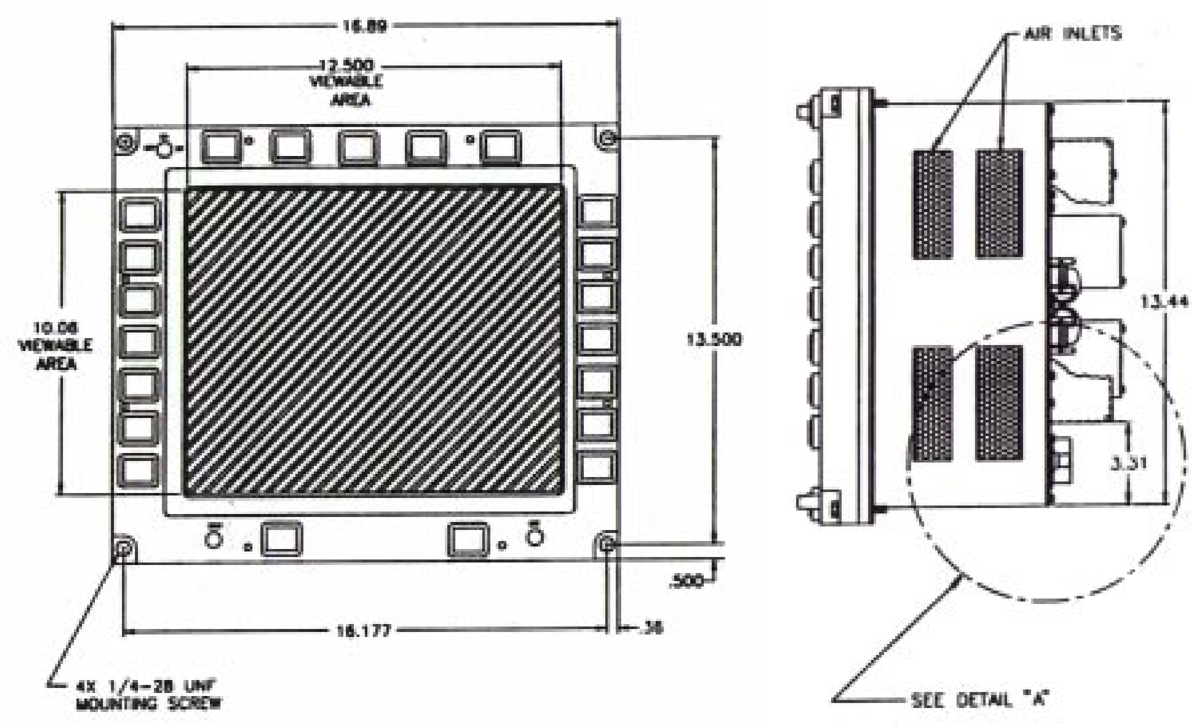

Figure 3. Schematic views of 16.1 in. AMLCD (front , side).

2.1.2. Interstate Electronics custom integrated 10.4 in. AMLCD

The 10.5 in. displays were packaged by Interstate Electronics and, unlike the other two sizes, involve no attempt whatsoever at ruggedization. These displays were acquired in 1994 and were used for a Wright Laboratory study comparing

LCDs to CRTs for avionics applications.[1] These displays are usually mounted in portrait mode so that they do not take up as much lateral room in the cockpit simulator.

2.1.3. Honeywell custom integrated 5.4 inch AMLCD

The 5.4 in. displays are made by Honeywell Technology Center (HTC) in Phoenix, AZ. HTC made these using Sharp LQ6RA52. They were acquired as a deliverable on a contract that Wright Laboratory had with HTC to develop ruggedization techniques for LCDs. These displays have a custom frame and bezel made from aluminum to optimize heat transfer away from the LCD glass stack. They have a custom Korry Electronics backlight capable of about 8000 fL luminance.

2.2. Display characterization

Objective evaluation was accomplished on these three different sized AMLCDs in the AFRL Aerospace Display Test and Evaluation Capability (ADTEC) at Wright-Patterson AFB in a series of photometric, colorimetric and radiometric tests to baseline their visual performance.[2-11] The results of these measurements at normal to the center of each display are presented in Table III. Measurements were made on two displays of each AMLCD size. Results for one are presented in Table III. There were not significant variations in the overall performance of the two units at either of the smaller sizes. However, the two 16.1 in. units differed significantly in their overall luminance due to a poor backlight in one; the overall luminance measured at normal to the center was 140 fL for one unit but just 70 fL for the other.

Table III. Characterization of the AMLCDs selected for use in the AMLCD Research Cockpit.

Location: center	**16.1 in.**			**10.5 in.**			**5.4 in.**		
Angle of view : 0^0	L	x	y	L	x	y	L	x	y
(from normal)	nt (cd-m^2)			nt (cd-m^2)			nt (cd-m^2)		
White (max)	94.10	0.344	0.398	105.00	0.326	0.364	439.00	0.369	0.446
Black	1.91	0.287	0.355	3.22	0.278	0.316	2.46	0.308	0.418
CR (dark ambient)	49.27			32.61			178.46		
Red	22.10	0.626	0.336	30.40	0.540	0.355	112.00	0.613	0.358
Green	70.20	0.306	0.631	61.90	0.313	0.510	297.00	0.320	0.625
Blue	37.40	0.148	0.143	19.40	0.163	0.177	48.80	0.157	0.202

3. USES OF THE AMLCD RESEARCH COCKPIT

The primary role of pilots is to control aircraft, although in commercial aircraft this job is often taken over by the flight management system. Control information includes attitude and power indicators. Even if pilots are not manually controlling the aircraft, they still need to know the flight status; therefore, performance information is of prime importance. An aircraft in flight is always proceeding to a particular destination, so navigation information is also crucial to pilots. Pilots are also concerned with the health of the systems aboard the aircraft. Even while systems are performing normally, system status information is of prime importance; if problem situations occur, emergency information is crucial. For military aircraft, additional information is required to keep pilots abreast of threats to the mission and the aircraft and the status of enemy forces. This knowledge is called tactical situation information. The challenge for the cockpit designer is to present all of this information in a manner that does not overload pilots' information processing and attention management abilities.

3.1 How early electro-optical (EO) display provided this information

In the early military and civilian E-O cockpits, the format of the information presented was, by and large, the same as that presented on the electro-mechanical (E-M) instruments. There are several reasons for this. The first is that the introduction of E-O displays into the cockpit was a radical departure from previous designs; therefore, in order to prevent "culture shock", the decision was made to emulate the same picture on the CRT that the pilot was used to seeing on his E-M instruments. This was a relatively safe strategy for display endorsement and certification purposes. Another reason that more advanced display formats were not used is that the symbol generator (the computer that draws the format) was not capable of drawing more complicated pictures. However, current developments in airborne graphics generators will make more detailed or advanced formats possible. Still another reason why E-O formats didn't differ from E-M instruments was that advanced formats had not been developed to the stage where pilots had complete confidence in them. As pilots become more experienced with E-O displays, cockpit designers can explore their potential by developing formats that represent a total paradigm shift from replicating E-M instruments.

3.2 Advanced graphic formats

The formats reviewed in this section are related to the previously discussed information needed by pilots. Specifically, control and limited performance information is provided by the Pathway-in-the-sky; navigation and tactical situation information is provided by the Tactical Situation Display and the overhead map; and systems' status and emergency information is provided by the Crew Alerting and Systems' Status Display.

3.2.1 Pathway-in-the-sky

The heart of the advanced flight display is the Pathway-in-the-sky.[12] The Pathway can take the place of both the flight path angle scale and the flight path marker symbology currently used on head-up displays (HUDs). The Pathway consists of a series of blocks configured to resemble a highway (Figure 4). In addition, a "follow me" aircraft appears at a particular distance above the path and acts as both a speed and altitude cue when pilots fly in formation with it. Additional symbology (e.g., airspeed and attitude indicators) may be added to enable the display to serve as a primary flight reference in compliance with MIL-STD-1787B.[13] The advantage of the path is that it gives pilots a means of determining what their 3-dimensional route will be in the future. Also, it tells them how to maintain their commanded airspeed in a very natural manner: by flying in formation with the follow me aircraft. Thus pilots can view the path in the distance and anticipate the turns, climbs, and dives. Today's HUDs only depict the route location at the present time and do not provide knowledge about future maneuvers. A head-down Pathway – not limited by the color capabilities and clutter issues associated today's HUDs – can show more information, such as restricted airspace in the vicinity of the commanded route. Note that in both cases the perspective is an egocentric or inside-out one. While perhaps not optimal from a global situation awareness (SA) standpoint, this perspective has been shown to be important in maintaining proper flight control when using a Pathway display.[14]

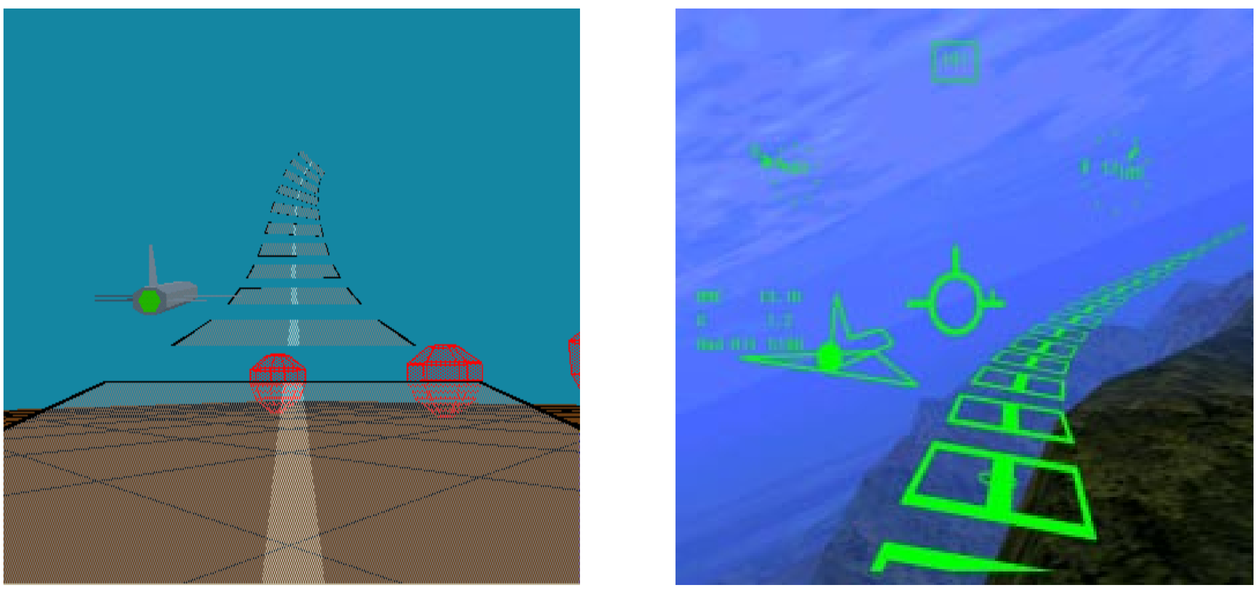

Figure 4. Pathway in the sky display, head-down example on the left, head-up example on the right.

3.2.2 Tactical situation display (TSD)

The TSD (Figure 5) portrays to pilots fused data regarding both navigation and tactical information. Through the use of a pictorial format that chunks the data, the TSD can reduce information overload and aid decision making. Unlike the Pathway display, the TSD is shown from an exocentric or outside-in perspective for greater SA. The TSD combines, in an outside-in perspective view, the aircraft symbol with terrain data and threat data. It gives pilots a look at the overall tactical situation as it is developing before them out to the horizon (e.g., 20 miles away). There is a pathway extending ahead of the aircraft that shows where the aircraft will go if pilots allow it to follow the pre-planned path. One of the issues faced in designing a perspective display is the elevation and angle of the viewpoint.[15] The viewpoint chosen for initial perspective displays was 1 mile behind and 1000 feet above the pilot's own aircraft; the lookdown angle was 30 degrees.[16] However, in future displays, operators will have a continuously adjustable viewpoint. The continuous elevation adjustment is analogous to riding in an elevator. The continuous lookdown angle is similar to standing on an observation

tower looking straight down to the earth, and then slowly raising your head until your gaze is level with the horizon. All of these views will be available to pilots.

The terrain can be color-coded to portray additional information to pilots. For instance, the ground that is below the current flight level can be green, and the ground at or above the current flight level can be red. In addition, ground-based threats, such as surface to air missile (SAM) and radar-directed anti-aircraft artillery (AAA) sites can be shown in perspective view and are also color-coded. The area of greatest potential lethality to the aircraft can be shown in red and areas of lesser lethality can be shown in yellow. Additional information can be given to the pilot about the status of each threat by further coding dimensions. Threat sites with known locations, but not active, can be shown as outline polygons only. Sites that are actively searching can be shown as filled-in solid polygons. Sites that are tracking the aircraft can be connected to the aircraft symbol with a vector. A site that has launched a weapon against the aircraft can be connected to the aircraft symbol by a blinking vector. In the last two conditions, a circle can be shown around the aircraft symbol, filled in yellow if on-board countermeasures are effectively countering the threat, and filled in red if countermeasures are not being effective. In all cases, the most likely interface option chosen by the cockpit designer will be to allow pilots to select or declutter the information portrayed on the TSD to match their mission, mission phase, and personal preferences.

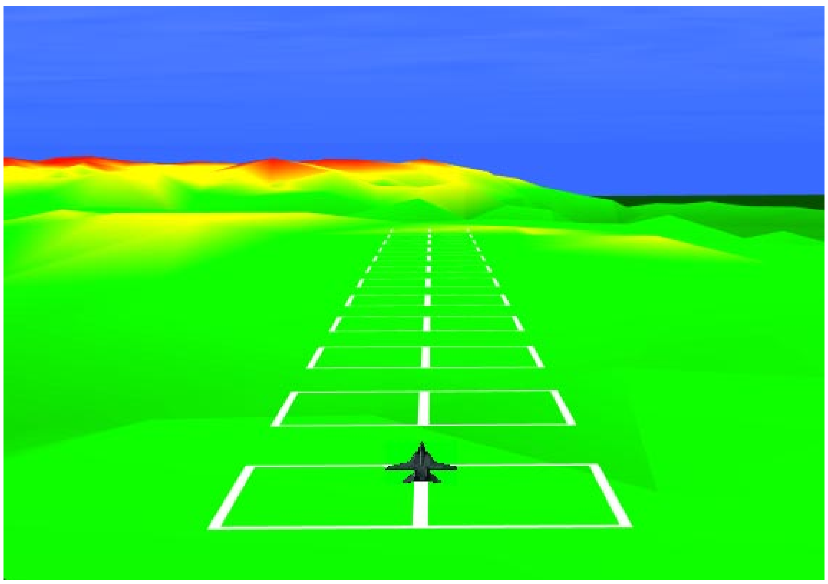

Figure 5. Tactical situation display decluttered during low-level approach to high terrain.

3.2.3. Overhead maps

One of the most demanding applications of an avionics display is the overhead map, used primarily for navigation and global situation awareness. The standard of comparison in terms of resolution and color capability is the paper map pilots now commonly carry with them in the cockpit. Figure 6 shows an example of a Tactical Pilot Chart (TPC), one of the overhead maps commonly used in the cockpit. Being able to incorporate an electronic display into the cockpit with resolution and color capabilities approaching that of printed material will, in addition to removing the inconvenience and workspace clutter of a physical map, allow pilots to alternate between north up and track up modes, zoom in and out to control the area displayed, and – if the map is more than a simple scanned-in bitmap – declutter information not relevant to the current mission or mission phase.

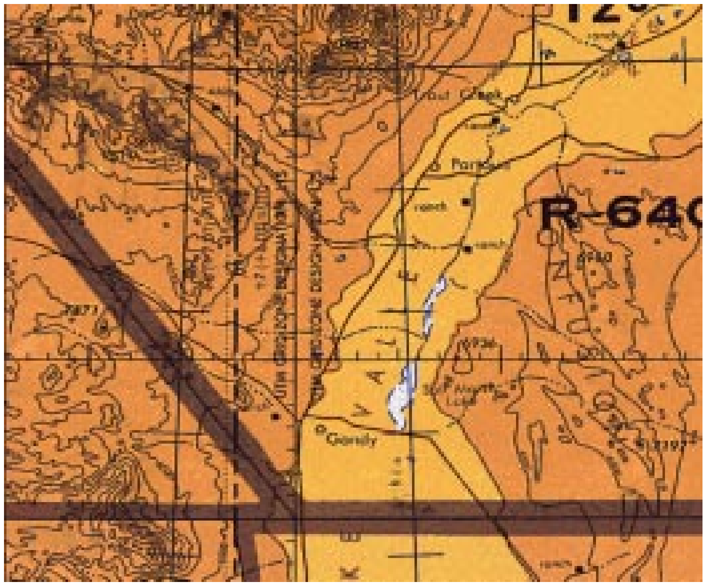

Figure 6. Tactical Pilot Chart format of an overhead map.

3.2.4 Crew alerting and system status format

An example of a new type of graphics display which gives the pilot the overall health of his primary systems is the Crew Alerting and Systems' Status (CASS) format (Figure 7). "CASS had several purposes: it provided full time dynamic display of fuel quantity and engine thrust; it alerted the pilot to system malfunctions; and it identified mission or flight safety implications of those malfunctions."[17] One of the unique aspects of this display is that it could not only show which system had failed (e.g., the left engine), but it could also show the mission impact. The mission impact is the overall effect of the particular failure on the successful completion of the mission. In the case of the engine failure, for example, the impact would be on the speed/performance aspect of mission performance. An additional display would then show the restrictions in speed/performance and impacts on times over target.

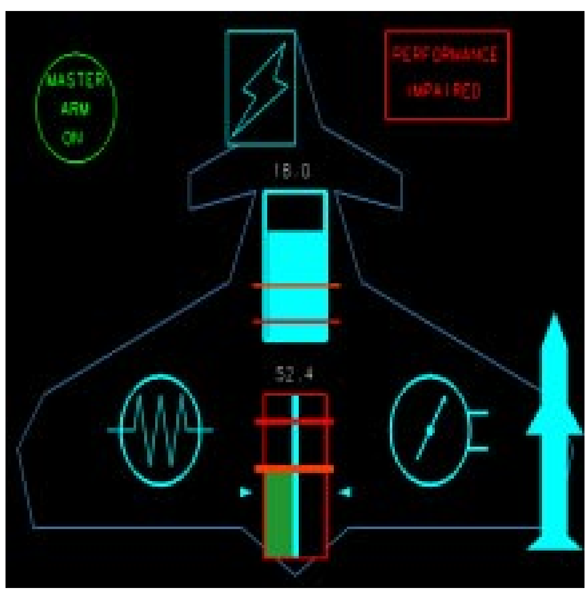

Figure 7. The Crew Alerting and Systems' Status display.

3.3. Rationale for AMLCDs in a research cockpit simulator

Cockpit simulators have traditionally used CRT display technology for electronic displays. This has been true even for the simulator for new aircraft cockpits that were destined to have only flat panel displays, AMLCDs in particular. For example, even the F-22 cockpit simulator uses CRTs in sizes approximate to those of the AMLCDs that were selected in 1992 at the EMD design decision point -- after which the space depth needed for the CRTs was given back for other system design purposes. In addition to size and weight considerations, affordability is another key AMLCD advantage over CRTs. The metric is life-cycle cost (LCC), which is dominated by mean time between failures (MTBF). The MTBF now being experienced by AMLCDs in 3-10 in. diagonal sizes in operational aircraft is over 10,000 hours, compared to approximately 300 hrs for bubble canopy fighter avionic CRTs. Luminance performance is also a plus with AMLCDs in comparison to CRTs. Despite the best efforts of DoD integrators and of specialized CRT manufacturers over the past 40 years, the most luminance achieved from an avionic CRT has been about 150 fL. The pilot needs 400 fL (some say over 1000 fL) from the display for the harshest sunlight readability situations encountered. AMLCD technology has been in use as an avionic display technology just ten years and several DoD integrators have demonstrated well over 200 fL. The technology has great potential for even higher luminances. It seems past time to move research cockpit work to flat panel displays. This is especially true as research programs advance from the lab to more high-fidelity mission simulations.

3.4. Human Visual Acuity vs. AMLCD Research Cockpit Capability

A key human factors engineering issue in the use of any avionics display is the legibility of the information displayed. The design eyepoint of the AMLCD Research Cockpit is 30 inches or 76.2 cm away from the central 16.1 in. AMLCD (in accordance with MIL-STD-1472E).[18] The display's pixel density of 102.4 color pixels per inch translates into 0.01 inches per pixel or 0.25 mm per pixel. One may use the following formula to calculate the visual angle subtended on the retina by one pixel.[19]

$$\alpha = \arctan\frac{S}{D} \tag{1}$$

where α is visual angle, S is the size of a pixel, and D is the distance from the object to the eye. Using this formula, one finds that one square pixel on this display will subtend 1.1 minutes of arc on the retina of the pilot when his/her eye is at the design eyepoint. This is very close to what is commonly called eye-limited resolution in the optics and human factors community. When tested with the Snellen eye chart used by most optometrists, normal human visual acuity is measured at 1 minute of arc. It should be noted that, while this is the limit of visual acuity for this test, it is not the same as saying that a display capable of one arcminute per pixel would be indistinguishable from reality: in other tests involving simple detection of a high-contrast line, the human eye has been found to be capable of detecting differences as small as 0.5 minutes of arc.[19] Nevertheless, this display resolution should be adequate to any task, including the overhead map display discussed previously. The same cannot be said of the side or top AMLCDs packaged by Interstate Electronics and Honeywell, respectively. In the case of these AMLCDs, the effective resolution at the pilot's eye would be roughly 1.5 arcminutes per pixel. This is functionally equivalent to asking a military pilot with 20/20 vision to rely on displays that only allow him/her 20/30 vision. Thus, neither of these are probably adequate for applications requiring fine detail (e.g., overhead map, small text in emergency checklists) and this was, in part, the reason for upgrading the simulator to allow it to include higher resolution CRTs.

4. DISCUSSION

The computer graphics revolution has removed the constraints on display designers, and they are limited primarily by their own creativity and their knowledge of human perception, information processing, and attentional phenomena in providing display formats for future aircraft cockpits. It is the coupling of high resolution flat panel displays with advanced graphics generators that will enable the crew station designer to produce formats that will dramatically improve the pilot's ability to obtain clearer, yet more complete, SA data in the tactical arena than is presently possible. These color, pictorial formats will also enable pilots to "stay ahead" of their mission, processing information proactively and devoting less time and attention to interpretation of displays.

With the increased exposure of the general population to computer-oriented products and particularly with the younger generations' often unquestioning acceptance of (and skills in) playing video games, it is fairly certain that pilots of the future will readily adapt to using advanced technology that appears similar in the cockpit. In fact, during many of the recent experiments to test advanced technology applications in the cockpit, the authors have noted that there is much greater acceptance of new technology among pilots today than there was even a few years ago. The reasons may be as subtle as technology "creep" -- the gradual acclimation of people (pilots) to an expanding technologically-oriented environment, or

they may be as striking as the Gulf War -- which demonstrated the advantages technology can provide for minimizing personnel and equipment losses. Whatever those reasons, it is crucial that the same kinds of technology continue to be used and improved, and that this technology be adapted to the unique requirements of pilots. It also seems clear that, in order for the displays and human factors research community to stay ahead of this trend, cutting-edge technology must be used in research cockpits to allow pilot expectations to be met. One cannot expect a pilot who has grown up in a world of constant, rapid technological advance – especially in the areas of display hardware and computer graphics – to be satisfied with anything less when he/she steps into a military cockpit, real or simulated. Through the development and testing of computer graphics formats now, along with cognizance of advances in display hardware and human factors engineering, the smooth transitioning of the next generation pilot can be assured and, along with it, the preeminence of the weapons systems he controls.

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